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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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BIBLIOGRAPHY AND REVIEW OF INFORMATION RELATING
TO THE HYDRODYNAMICS OF SEAPLANES

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ADVANCE CONFIDENTIAL REPORT

BIBLIOGRAPHY AND REVIEW OF INFORMATION RELATING
TO THE HYDRODYNAMICS OF SEAPLANES

By James M. Benson and Jerold M. Bidwell

SUMMARY

A bibliography and a review of information relating to the hydrodynamics of seaplanes have been presented. Data and conclusions obtained from the references in the bibliography have been correlated to present in qualitative form a summary of the status of knowledge pertaining to the hydrodynamics of seaplanes and to point out the need for further research. Characteristics of conventional hulls and floats are discussed to show the effects upon performance of changes in design parameters such as dead rise, depth of step, and angle of afterbody keel. A separate section has been devoted to special problems relating to floats for seaplanes. Other topics discussed include lateral stabilizers, aerodynamic and propulsive considerations, unconventional configurations, hydrofoils, and piloting and handling.

The arrangement of the bibliography in general is similar to that of the text. References on flying-boat hulls, planing surfaces, and seaplane floats, however, have been listed separately in the bibliography. Reference material pertaining to impact loads has been included in the bibliography although the subject has not been reviewed. Information on experimental procedures used to obtain the results discussed in the text may be found in the references in the concluding section of the bibliography.

INTRODUCTION

An increasing demand for information relating to the hydrodynamics of seaplanes has indicated the need for a compilation of existing scattered data. The present report, which has been prepared in an attempt

to fill this need, is in the form of a bibliography and a brief review of the subject. Wherever possible the present status of the various phases of hydrodynamic research is indicated and the need for further research is pointed out although an extensive treatment of the subject has not been attempted. Complete data and the detailed development of the important conclusions may, in general, be found in the reports listed in the bibliography. In some instances, however, previously unpublished data and data from sources not suitable for reference purposes have been included. Reports that are not generally available for distribution, either for security or proprietary reasons, are marked with an asterisk in the bibliography.

The material presented herein has been organized in a way that isolates insofar as practical the effects of design parameters such as dead rise, depth of step, and angle of afterbody keel in preference to more general subjects such as resistance, stability, and air drag. A list of references pertaining to impact loads has been included in the bibliography although the subject has not been discussed in the text. Properties of both hulls and floats are discussed under the heading "Conventional Hulls and Floats" and special problems relating to floats are taken up under the heading "Floats for Seaplanes."

Acknowledgment is made to Boeing Aircraft Company, Consolidated Vultee Aircraft Corporation, Edo Aircraft Corporation, and The Glenn L. Martin Company for furnishing copies of engineering reports pertaining to flight tests of seaplanes and the application of the results of model tests to design practice. The following members of the staff of the Langley Hydrodynamics Division gave material assistance in correlating the large amount of data: Joe W. Bell, John R. Dawson, John W. Ebert, Jr., Leo F. Fehlner, Douglas A. King, Norman S. Land, Roland E. Olson, John B. Parkinson, and Henry B. Suydam.

CONVENTIONAL HULLS AND FLOATS

Over-All Proportions and Shape of Flying-Boat Hulls

The hull of a flying boat performs the functions of fuselage, flotation gear, and landing gear. The

over-all proportions and shape of a hull result from a harmonious combination of the proportions and shapes of the various components designed for each function or combination of functions. The over-all form is important in itself mainly in connection with the fuselage and flotation functions rather than with the detailed hydrodynamic characteristics during motion on the water. A hull is best designed by taking into consideration its requirements - that is, space for accommodation, seaworthiness, tail-length, etc. - rather than by trying to fit the requirements into a preconceived over-all form.

Maximum beam.- The maximum beam of a flying-boat hull is determined somewhat by the buoyancy required and in transport airplanes by the width required for accommodation of the pay load. The beam loading is properly regarded as a very important criterion and must be selected to suit the intended service.

Over-all length.- The over-all length of the hull is approximately made up of the length of the forebody required for accommodation ahead of the center of gravity and for adequate seaworthiness underway plus the predetermined distance from the center of gravity to the tail surfaces. In contemporary hulls, the over-all length is usually greater than the sum of forebody and afterbody lengths. The additional length is the tail extension.

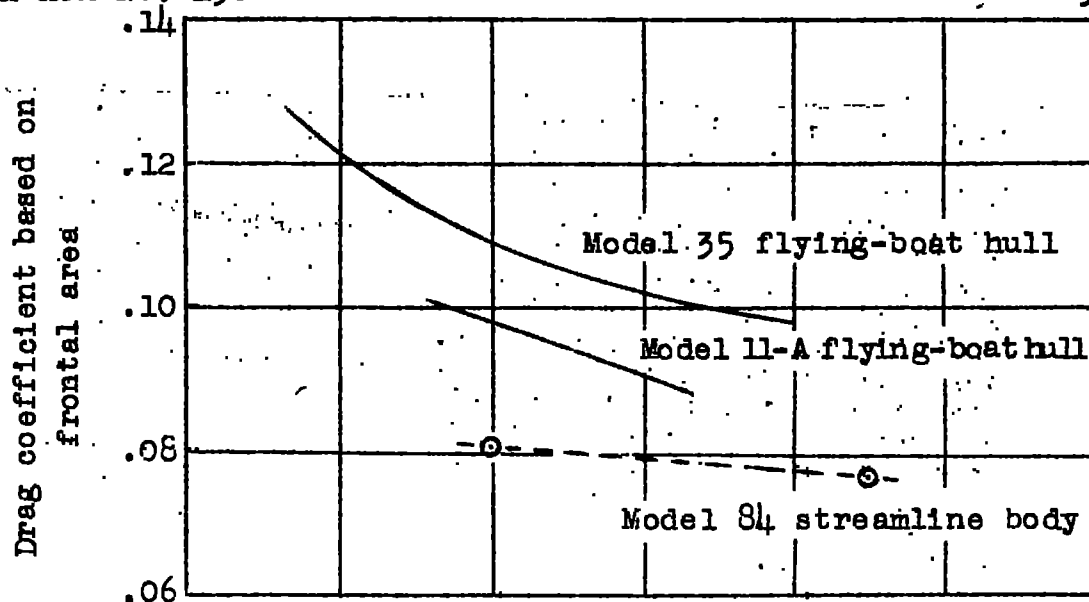
Over-all length-beam ratio.- The over-all length-beam ratio is fairly well determined by the type and configuration of the airplane. It is possible, however, to vary the ratio for the same design and still maintain the same degree of seaworthiness by varying the beam loading, the forebody length-beam ratio, and the size of the tail surfaces. The effect of such a variation on the aerodynamic drag is included with the hydrodynamic effects under "Hull Loading and Length-Beam Ratio."

Height and height-beam ratio.- The height of the hull is usually greater than that required for accommodation and aerodynamic configuration in order to provide sufficient spray clearance for the propellers and aerodynamic surfaces. It is possible, however, to use different heights for different beam loadings and still maintain the same degree of seaworthiness. Most present-day multiengine flying boats are characterized by high beam loadings combined with high height-beam

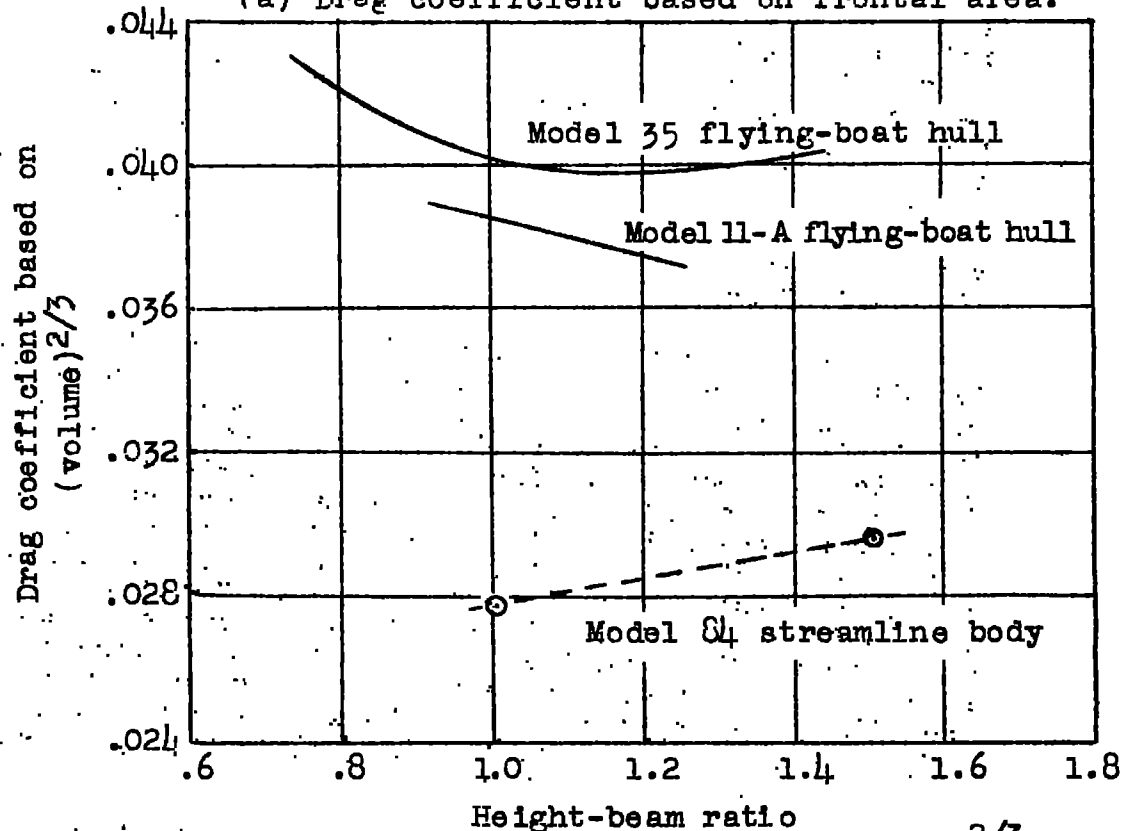
ratios, and some authorities conclude that this combination is preferable from all standpoints (reference 18). The PBV-5 (Catalina), however, is one example in which low beam loading is combined with low height-beam ratio of the hull, the wing being carried on a pylon, yet is considered exceptionally seaworthy. Hydrodynamic tests of a related family of powered dynamic models having systematic variations in height-beam ratio combined with appropriate values of length-beam ratio are required to determine whether there is an optimum height-beam ratio for a given class of airplane.

Tests in the Langley propeller-research tunnel of two models of flying-boat hulls have shown that the drag coefficient based on frontal area decreases with an increase in the height of the hull for a given beam and length although the drag actually increases (reference 43). Coombes and Clark (reference 18) have concluded from these data that high values of height-beam ratio are preferable. The data are shown in figure 1(a) as curves of drag coefficient based on frontal area plotted against height-beam ratio, along with similar data from tests of a streamline body in the Langley 8-foot high-speed tunnel which show a similar trend (reference 70). The same data presented in figure 1(b) as curves of drag coefficient based on the two-thirds power of the hull volume plotted against height-beam ratio, however, indicate a different conclusion. The drag coefficient based on volume for model 35 is at a minimum near a height-beam ratio of 1.2 while the trend for the streamline body is reversed. In general, it would be reasonable to expect that the minimum drag for a given volume would occur near a height-beam ratio of 1.0.

Shape.— When the over-all proportions and dimensions of the hull have been determined, the drag becomes a function of the detailed shape. Below the chines the shape must have suitable hydrodynamic characteristics but otherwise should be smooth and fair in three dimensions for the minimum of interference to the flow of water or air and for ease of construction.



(a) Drag coefficient based on frontal area.



(b) Drag coefficient based on $(\text{volume})^{2/3}$.

Figure 1.- Variation of drag coefficient with height-beam ratio for flying-boat hulls and streamline body.

As an indication of the relative "cleanness" of flying-boat hulls, Hartman (reference 43) compared their drag coefficients with the drag coefficient of an airship hull at the same Reynolds number. The best hull with a tail extension had a minimum frontal-area drag coefficient of 0.092 as compared with the airship drag coefficient of 0.052; hence, if all practical considerations are neglected, it would be possible to reduce the drag of this hull about 47 percent. The minimum frontal-area drag coefficient of a very clean hull (fig. 2) as measured in the Langley two-dimensional low-turbulence pressure tunnel (reference 70) was found to be 0.080 as compared with a skin-friction drag coefficient of 0.056 at the same Reynolds number; the increment not chargeable to skin friction was therefore 42 percent of the total.

A closer estimate of increment chargeable to the function of the hull as a landing gear is given in reference 79, in which the minimum drag coefficient of a streamline hull was shown from tests in the Langley 8-foot high-speed tunnel to be about 20 percent greater than that of either the straight or the warped streamline body from which it was derived. A similar comparison was made in reference 18 which indicated that, for the hull considered, the minimum drag coefficient was 22 percent greater than that of the warped streamline body from which it was derived.

In references 18, 70, and 79 the general premise is advanced that the best over-all shape for a hull is one for which the departures from a streamline body of revolution are kept at a minimum consistent with hydrodynamic requirements. Increasing the height of a well-faired bow has only a small adverse effect on the drag; increasing the height of the stern by warping the basic form but holding the afterbody position fixed has a larger adverse effect (reference 79). Warping a streamline body at the stern is shown in reference 79 to have no adverse effect on the minimum drag but increases the angle of minimum drag as would be expected. In reference 18, however, warping the tail of the streamline body is said to increase the drag 13 percent, presumably at the same angle of attack.

In reference 43 the beneficial effect of a rounded deck for the same frontal area is estimated to be a reduction in minimum drag of 21, 23, and 26 percent,

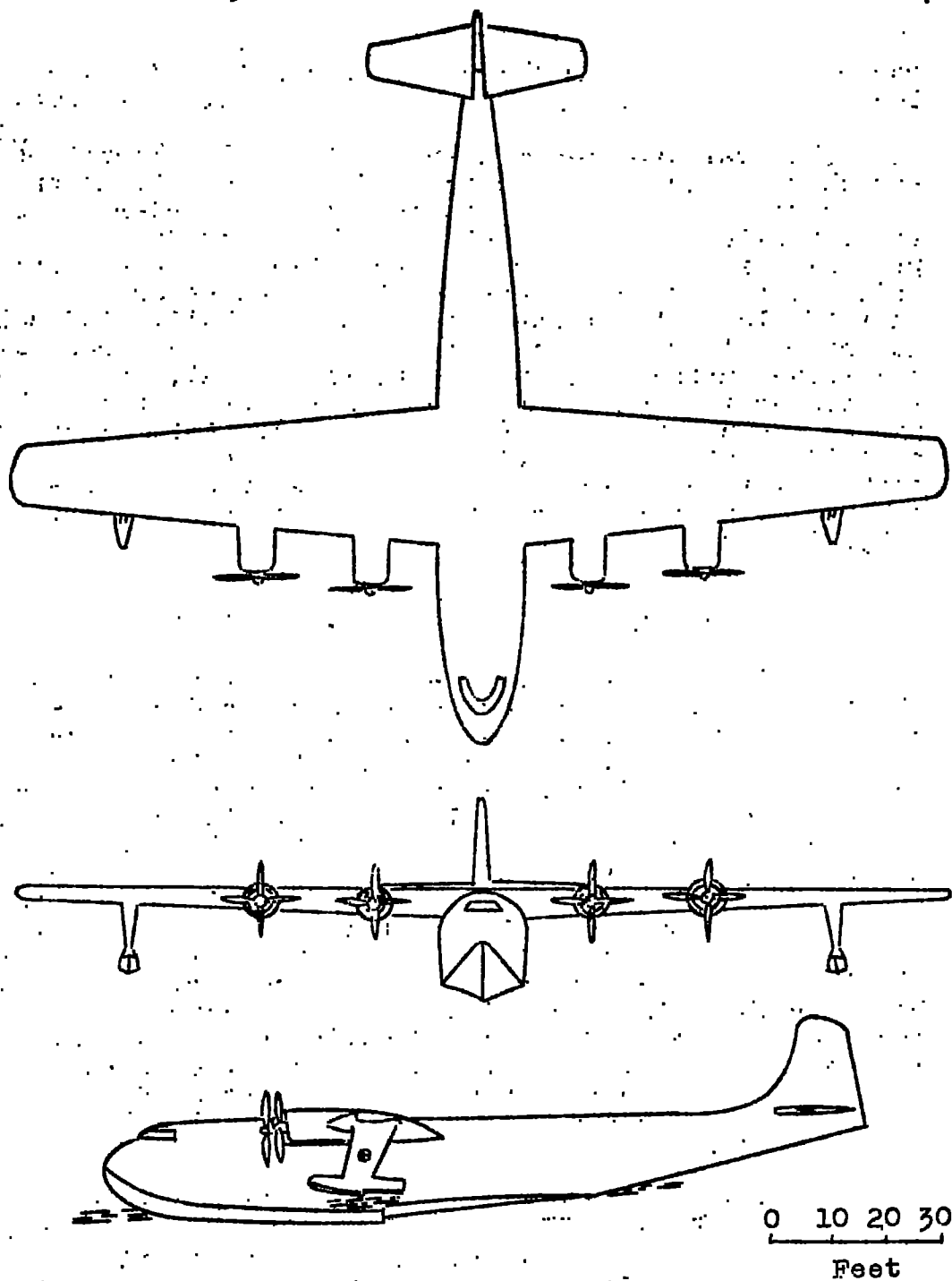


Figure 2.- Conventional flying boat for transport service with hull designed for low air drag (reference 70).

respectively, for the three models considered. The increase in drag attributed to the windshield is small.

The available data on the effects of proportions and shape indicate that careful design and attention to the shape of the hull are essential in order to keep the parasite drag at a minimum. The added drag of properly arranged chines and steps becomes of the same order of magnitude as that due to roughness and unavoidable protuberances on the actual hull. Radical departures from the form for minimum drag or forms having excessive surface area will not, in general, be desirable for high-performance airplanes regardless of their hydrodynamic advantages (reference 70). (Fig. 2 shows a flying boat of conventional arrangement for transport service with a low-drag hull having suitable hydrodynamic characteristics for a gross weight of about 120,000 lb.)

Hull Loading and Length-Beam Ratio

The loading of a flying-boat hull or a seaplane float is usually expressed in terms of load coefficient C_A , which is based upon beam as the characteristic dimension. Load coefficient provides a good scale for the load on hulls having comparable length-beam ratios and for any hull in the planing condition, in which wetted length is a dependent variable. At low speeds, however, when the bow of the hull is wetted, load coefficient loses most of its significance in the comparison of hulls of different length-beam ratios. Because of the close relationship between load coefficient and length-beam ratio, it is necessary to consider both variables in discussion of the load-carrying capacity or the performance of hulls at low speeds. The length and beam of the forebody are considered the most important dimensions because the dimensions of the afterbody must be made approximately in proportion to those of the forebody.

Effects of load with hull proportions held constant.- The effects of load have been investigated in numerous general tests of flying-boat hulls and in overload tests of most specific designs. Data from these sources show

the effects of load on the performance of flying-boat hulls of conventional shape and proportions. Increasing the load coefficient

- (a) reduces load-resistance ratio Δ/R at hump speed
- (b) increases Δ/R at speeds near get-away
- (c) raises both the upper and lower trim limits of stability
- (d) usually decreases the range of stable locations of the center of gravity
- (e) increases difficulty of directional control at low speeds (Several cases are known in which the load of a flying boat has been limited by directional instability.)
- (f) increases the height and intensity of spray

Length-beam ratio.- A criterion relating the gross-load coefficient C_{Δ_0} of a flying-boat hull to the length-beam ratio of the forebody has been established by analysis of the spray characteristics of existing flying boats (reference 69). This analysis shows that the load capacity of a hull of conventional proportions varies with the first power of the beam and the second power of the length of forebody. The maximum gross-load coefficient for the hull of a multiengine flying boat may be determined by the following expression:

$$C_{\Delta_0} = k \left(\frac{L_f}{b} \right)^2$$

where L_f is the length of forebody, b is the beam, and k is a nondimensional criterion ranging from 0.0525 for hulls with light spray to 0.0975 for hulls with excessive spray.

In references 17 and 18 it was assumed that uniform seaworthiness may be maintained by varying loading so

that the draft of the main step at rest remains a constant proportion of the length of the forebody of the hull. From data in these reports for over-all length-beam ratios from 5.5 to 10.0, the following expression may be obtained:

$$C_{\Delta_0} \propto \left(\frac{L}{b}\right)^{2.5}$$

The approximate relationship

$$C_{\Delta_0} \propto \left(\frac{L}{b}\right)^2$$

has also been supported by Davidson and Locke (reference 20) on the basis of conclusions reached in general tests. Tests made in Langley tank no. 1 (reference 8) have shown that holding C_{Δ_0} proportional to L/b gives very conservative loading at high values of L/b .

Resistance data from systematic investigations of length-beam ratio are available in references 8, 17, 18, 20, 91, and 143. The effects of length-beam ratio on the trim limits of stability are included in reference 20. These references include data on spray without power, or notes on observations of spray, but no systematic spray investigations have been made with powered models of different length-beam ratios.

When the load of a hull is held constant and the length-beam ratio is varied by changing length or beam, the effects of length-beam ratio are usually obscured by the effects of changing the size of the hull. In variations of this type, the effects of increasing length or beam are in the same direction as those of reducing load without changing dimensions. The effects of increasing the length of a powered dynamic model have been reported in reference 49.

Analysis of data from references 8, 20, and 143 indicates that when C_{Δ_0} is proportional to $(L/b)^2$

the spray and resistance characteristics are not impaired if length-beam ratios are increased from 5.5 to 10.5. From the same analysis the length-beam ratio for optimum resistance characteristics depends upon the lines of the hulls considered. There is some indication that the ratio of over-all length to beam beyond which no further gain is obtained in hydrodynamic characteristics is between 9 and 10 (references 17 and 18). The best trim at the hump decreases as length-beam ratio is increased. It has been shown that the stable range of trim is reduced with increasing length-beam ratio (reference 20). Recent tests of a family of models derived from the proportions of the XPBB-1 airplane indicated that the stable range of center-of-gravity locations was about the same for a length-beam ratio of 9 as for the basic value of 6.3. The principal advantage of high length-beam ratio appears to be that of reducing length-beam product and thereby reducing the size of the hull.

Dead Rise

For most present-day flying boats of American design, the angles of dead rise measured adjacent to the forebody keel near the step lie between 20° and 25° . Some recent British designs employ an angle of dead rise of as much as 30° (reference 35). Angles within the range of 20° to 30° probably represent the best compromise for over-all performance.

Data on the effect of dead rise are available from tests of hulls and floats (references 11, 18, 22, 23, 26, 140, 143, and 254) and from tests of planing surfaces (references 108, 109, 116, and 119). These data are in general agreement on most of the effects of dead rise. Increasing the angle of dead rise

- (a) has little effect on hump resistance in the range from 15° to 30°
- (b) increases resistance at speeds above hump speed
- (c) increases positive trimming moment at planing speeds
- (d) raises the lower trim limit of stability
- (e) reduces the impact loads

It is believed that increasing the angle of dead rise raises the upper trim limit of stability, as indicated in references 23 and 108, but reference 22 shows a slight lowering of the upper limit with an increase from 20° to 30° in angle of dead rise.

Increasing the angle of dead rise within the range of 15° to 30° generally reduces the spray but tests with planing surfaces (reference 119) indicated an increase in spray with increasing angle of dead rise. Model tests of a flying-boat hull with slightly arched cross sections (negative angle of dead rise) showed excellent spray characteristics and low resistance (reference 3).

The available information on the effect of angle of dead rise on air drag is limited and is not in agreement. Langley wind-tunnel tests of three sea-plane floats having angles of dead rise of 20° , 25° , and 30° (reference 140) show increasing air drag with increasing angle of dead rise, while a British compilation of data (reference 18) indicates that air drag decreases with increasing angle of dead rise.

Tests of powered dynamic models of a flying boat (reference 23) indicate that the landing stability is improved by increasing the angle of dead rise from 20° to 25° .

Forebody

Bow.—Compromises in the shape of the bow are frequently made to accommodate bombardiers' windows or armament in military designs and may be made to favor seaworthiness, air drag, or simplicity of construction. In general, however, certain principles should be followed in order to provide seaworthiness and resistance characteristics consistent with operational requirements, with a minimum of departure from the best aerodynamic form. For a hull that is developed about a streamline body of revolution, the air drag will be at a minimum if the chines are located in planes passing through the axis of the basic body of revolution (reference 79). (See fig. 3.)

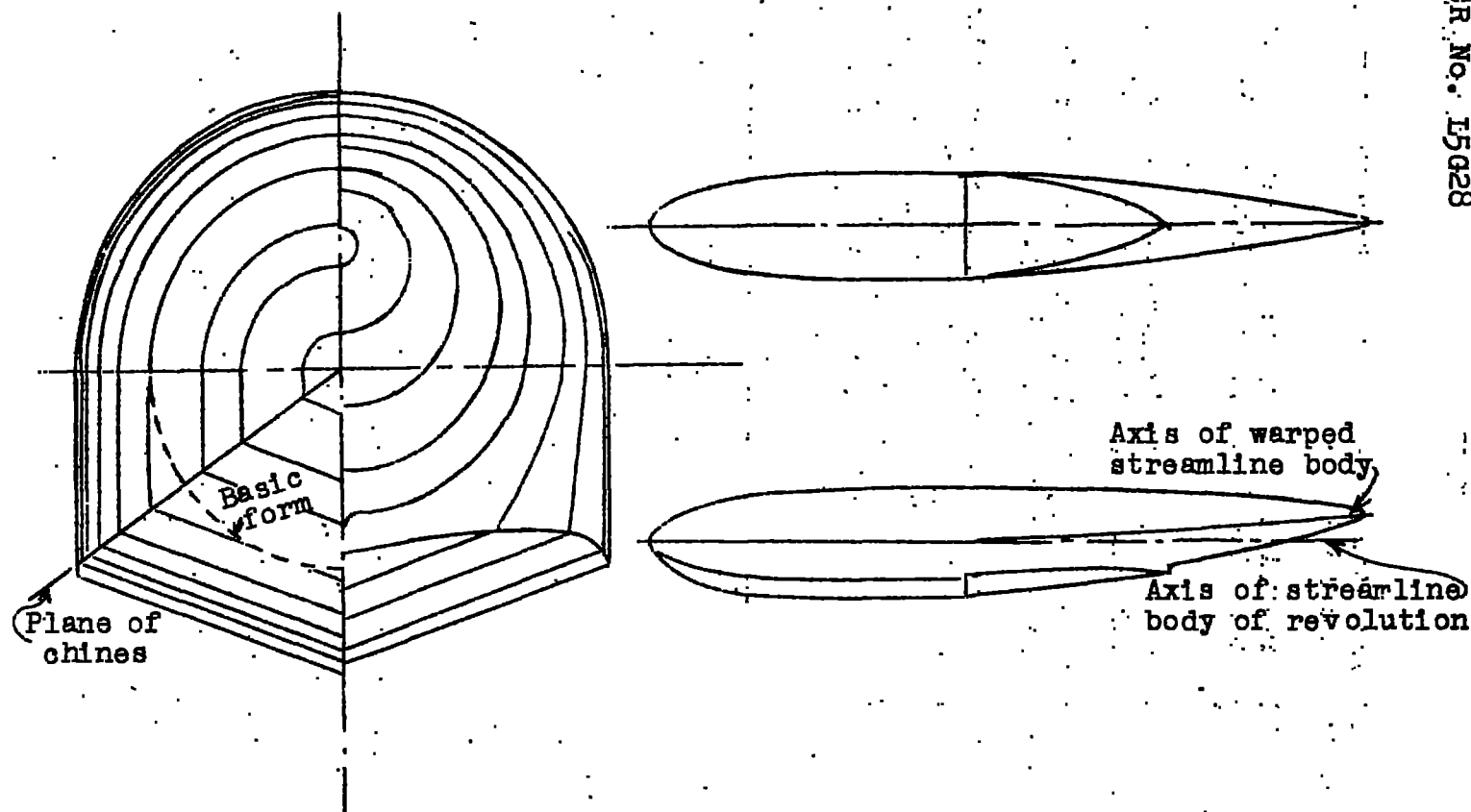


Figure 3.- Hull developed about a streamline body of revolution.
(From reference 79.)

Effects of changes in the shape of the bow are summarized as follows:

(1) Insufficient buoyancy forward results in low trim and excessive bow spray at low speeds (reference 79).

(2) Increasing the "fineness" of the bow below the chine reduces bow spray (references 55 and 79).

(3) Increasing the height of the bow increases the air drag (references 79 and 139).

(4) Rounding the chines (in cross section) at the bow will severely increase the bow spray and will reduce the air drag at large or low angles of attack (reference 79). At angles near those for the minimum drag of a suitably designed hull, rounding the chines has no significant effect on the air drag (references 58 and 79).

Longitudinal curvature of planing bottom.- It is generally considered desirable that the forebody bottom have no longitudinal curvature for some distance forward of the main step. A rough rule often quoted is that the buttocks should be straight and parallel for about 1.5 beams forward of the step in order to obtain satisfactory spray, resistance, and stability characteristics (reference 70).

The more significant effects of longitudinal curvature of the planing bottom near the step are:

(1) Convex curvature of the buttocks causes negative pressures at planing speeds that may significantly reduce dynamic lift and impair the efficiency of the hull (references 68, 90, and 91).

(2) Longitudinally concave buttocks have little effect on hump resistance but reduce the resistance and volume of the spray at high speeds (references 67 and 119).

(3) Concavity that is localized near the step in a length of the order of one-half the beam or less may cause extremely severe instability (references 12 and 61).

Warping of bottom surfaces of forebody.- Systematic investigations of warped planing bottoms having straight buttocks have been reported in references 22 and 55.

Warping the forebody bottom (dead rise increasing toward the bow) lowers the lower trim limit of stability but the change at speeds just beyond the hump is relatively small. This lowering of the lower trim limit is accompanied by a lowering of the trim track, which may result in a change in the stable range of center-of-gravity positions. The upper trim limit is lowered slightly but not as much as the lower limit. Increasing the warping increases the resistance at the hump and at high speeds. The bow spray is improved somewhat by increased warping, but it is also shown in references 55 and 79 that by confining the warping to the forward portions satisfactory bow spray characteristics may be obtained without compromising the planing characteristics.

Chine flare.- Tests of a large number of variations of chine flare (reference 9) have shown that good spray characteristics may be obtained with flare on the planing bottom confined to a width of about 8 percent of the beam and ending with a horizontal or slightly downward direction at the chine. Wide variations in the width, radius, or final downward angle of the flare, however, cause relatively small differences in the spray or resistance characteristics. Chine flare reduces the height of the forward part of the spray where the spray leaves the model above the water level but has little effect on the spray where the chine of the model is below the water level. Chine flare has little effect on resistance at the hump and at speeds near get-away; but the addition of chine flare, by reducing the height of the chines above the keel, causes a slight reduction in resistance at speeds just beyond the hump. Chine flare has little effect on the air drag of a hull if the chines are located approximately along the natural lines of air flow (reference 79).

External chine strips.- Chine strips may take the form of relatively thin projections extending outward or downward from the chines (references 23, 43, 76, 98, 140, and 256) or of sponsons, as shown in figure 4, that increase the beam and have a depth approximately equal to the width (references 49 and 60). Strips are sometimes incorporated instead of chine flare to improve the spray characteristics without involving complicated construction. In most cases, however, external chine strips of either type are added to improve the hydrodynamic performance of overloaded hulls or hulls with insufficient chine flare.

Strips having a width of about 3 percent beam and downward angles of 10° to 45° improve the spray characteristics and cause some reduction in resistance (references 45, 98, and 256). Wind-tunnel tests have shown, however, that such strips increase the air drag of hulls by 8 to 20 percent (references 43, 140, and 256).

Sponsons on the bow and the forward portion of the forebody have been used to control the spray of heavily loaded hulls (references 49 and 60). Model and full-size

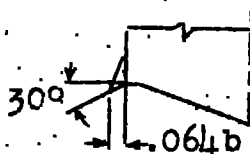


Figure 4.- Sponsons extending outward and downward.

tests have indicated that sponsons greatly increase the overload capacity of flying boats by reducing the bow spray at heavy loads. Like the thinner chine strips, the sponsons significantly increase the air drag and are suggested for use only when it is necessary to increase the load-carrying capacity of an existing hull. Recent tests (reference 45) have shown that vertical spray strips projecting about 3 percent of the beam downward from the chine (fig. 5) are about as effective as sponsons in

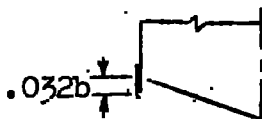


Figure 5.- Spray strips extending vertically downward from chine.

controlling spray. Information regarding the air drag of vertical strips is not available and the value of retracting this type of spray strip is questionable.

Longitudinal steps.- Longitudinal steps combined with flat surfaces having little or no dead rise were used on the forebodies of a number of flying boats some years ago. This type of bottom, in contrast with a conventional V-bottom, increases the resistance at low speeds and decreases the resistance at speeds near get-away (reference 4). Apparently no data are available regarding the effect of an arrangement of this type on dynamic stability.

One model has been investigated to determine the effect of reversed lap strakes, similar to the clinker-built arrangement of ship planking (fig. 6), added to a planing bottom of the forebody of conventional form and proportions (unpublished data). Resistance tests were made of the model complete with a conventional afterbody.

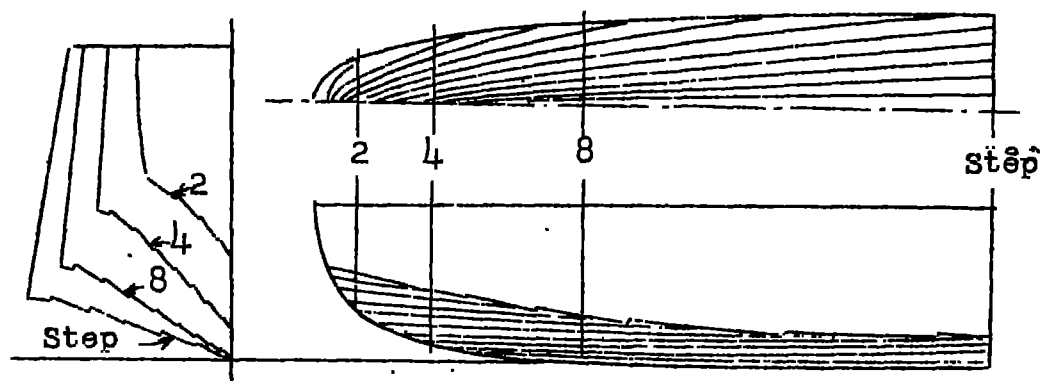


Figure 6.- Arrangement of longitudinal steps for NACA model 204. Depth of longitudinal steps, 1 percent of beam.

These strakes had negligible effect on the resistance at the hump but caused some reduction in resistance at higher speeds. The spray from the model with lap strakes was more finely broken up than that from the parent model but had about the same volume and height. The effect on dynamic stability has not been investigated.

Another variation of longitudinal steps has been tested on a powered dynamic model (reference 61). This modification consisted of a triangular strip on either side of the planing bottom forward of the step, as shown in figure 7. A depth of step of 11.5 percent of the beam

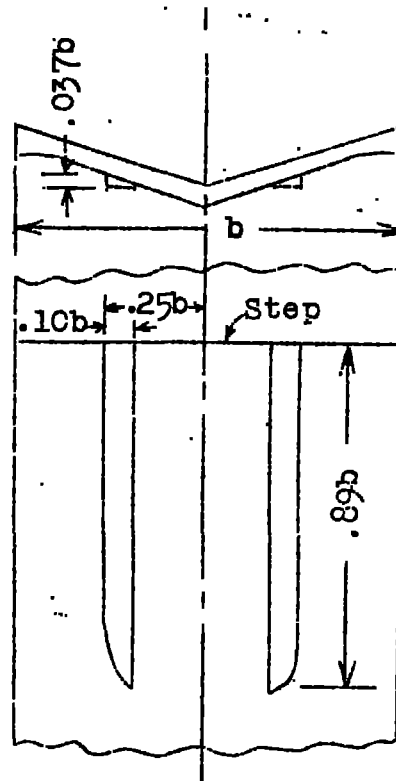


Figure 7.- Triangular strip added to planing bottom.

was required for adequate landing stability without the longitudinal steps. Longitudinal steps of the dimensions shown provided adequate landing stability when used in conjunction with a depth of step of 5 percent of the beam. It was also found that longitudinal steps of the same type but of larger size provided adequate landing stability with a depth of step of as little as 2 percent of the beam. With this configuration the strips had a cross-sectional area equivalent to an increase in depth of step of less than 1 percent of the beam so that the combined cross-sectional area of step and strips was less than half

the area normally required for sufficient ventilation during take-offs and landings.

Fluted bottoms.- Model tests (references 25 and 264) have indicated that the substitution of a fluted bottom (fig. 8) for a conventional V-bottom causes some reduction in spray and a reduction in resistance at high speeds but causes little change in resistance at low speeds and

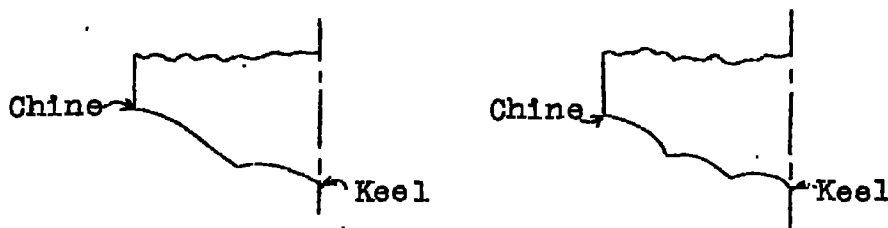


Figure 8.- Examples of fluted bottoms.

at the hump. The effects of flutes on dynamic stability have not been investigated but no adverse effect has been observed on full-size application. The principal advantage of flutes appears to be that of improving the structural efficiency.

Bottom roughness.- The increase in friction coefficient of a planing surface with rivet heads is directly proportional to the height of the rivet head above the surface. The order of merit of commonly used rivet heads in relation to low water resistance is: flush countersunk, oval countersunk, brazier, and round (reference 101).

With a $\frac{1}{3.5}$ -full-size seaplane model, the increase in

total water resistance caused by round-head rivets varied from 5 to 20 percent at hump speed and from 15 to 40 percent at high speed. The use of round-head rivets increases the total air-plus-water resistance of a single-float seaplane less than 5 percent at hump speed but as much as 25 percent at high speed. If the total resistance is calculated by Froude's law, it is found to be 2 percent higher at hump speed and 8 percent higher at planing speeds than that calculated by taking into account the effect of scale on frictional resistance (reference 138). Considerable difficulty has been experienced by service

organizations in maintaining watertightness with flush rivets of the type currently in use.

Afterbody

A primary function of the afterbody is to provide buoyancy and planing area aft of the center of gravity so that trims at rest and at low speeds are acceptable for practical operation. At speeds just before the hump and at hump speeds, the dynamic lift developed by the afterbody planing surface is one of the principal forces that controls the trim and, therefore, the water resistance. At planing speeds, the spray that strikes the afterbody increases the water resistance and changes the trimming moments. Take-off and landing instabilities that occur at high speeds and trims are associated with the position and form of the afterbody.

In general, changes in the afterbody that increase the afterbody clearance increase the static trim, increase the hump trim and resistance, decrease the high-speed resistance, shift the peak of the lower trim limit to lower speeds and higher trims, and also raise the upper trim limits. The trim tracks (variation of trim with speed) are shifted in the same direction that the trim limits are changed. In tests at the Langley tanks, no combination of conventional forebody and afterbody planing surfaces has been found that eliminates either the lower or the upper trim limits of stability or that suppresses the upper trim limit at high speeds.

Afterbody length.- An increase in afterbody length lowers the lower trim limits of stability at hump speed and lowers the upper trim limits (references 21, 22, 23, 48, 61, and 100). For a given depth of step and angle of afterbody keel, landings are more stable with a short afterbody than with a long afterbody (references 48 and 61). The depth of step required for the landing stability of a model with an angle of afterbody keel of 6.2° was approximately 8 percent beam for an afterbody length-beam ratio of 1.7 and approximately 13 percent beam for an afterbody length-beam ratio of 3.2 (unpublished data).

An increase in afterbody length without any change in forebody length decreases the hump trim and resistance (references 21 and 22) and may sometimes increase the spray in the propellers. Experience has shown that .

decreasing the trim reduces spray in the region of the flaps (reference 23). The tests described in reference 23 indicated that an increase in the length of the afterbody decreased but did not remove the directional instability at low speeds.

Angle of afterbody keel.- An increase in the angle of afterbody keel raises the lower trim limits at low speeds and raises the upper trim limits (references 21, 22, 48, 93, and 100). For a given depth of step and length of afterbody, landings are more stable with a low angle of afterbody keel than with a high angle of afterbody keel (reference 48). The depth of step required for landing stability of a model with an afterbody length-beam ratio of 2.7 was approximately 9 percent beam for an angle of afterbody keel of 4.8° and approximately 14 percent beam for an angle of afterbody keel of 9.3° (unpublished data). For some comparisons involving changes in both depth of step and angle of afterbody keel, the angle between the forebody keel and a line joining the step and sternpost, called the sternpost angle, is a useful parameter (reference 22).

In tests of three series of models (references 1, 11, and 79) an increase in angle of afterbody keel from 4° to 9° increased the free-to-trim hump resistance approximately 25 percent and the best-trim hump resistance approximately 15 percent.

Low angles of afterbody keel decrease the static trim, increase the tendency for spray to come over the bow at very low speeds (reference 55), and decrease the hump resistance at low speeds (reference 11).

Aerodynamic drag measurements (reference 43) indicate that differences in drag are practically negligible for angles of afterbody keel of 6° or less. At larger angles the aerodynamic drag increases appreciably.

Afterbody warping.- Effects of systematic changes in warping have not been extensively investigated. From the more or less isolated investigations that have been made the following results are of interest:

(1) Warping in a manner that decreased the angle of dead rise at the sternpost reduced the hump trim and resistance (reference 79).

(2) Warping in a manner that increased the angle of dead rise at the sternpost from 0° to 30° , with straight

buttock lines, raised the lower trim limit at hump speeds and raised the upper trim limits (references 21 and 22). Increasing the angle of dead rise at the sternpost of a dynamic model from 20° to 30° raised the lower trim limit at low speeds, did not affect the upper trim limits except at low speeds, and slightly reduced the yawing instability at speeds below the hump (unpublished data from Langley tank no. 1).

(3) Increasing the angle of dead rise to a maximum near the midlength of the afterbody has not significantly affected the landing stability of models (references 23 and 61). It should be noted that tests of a full-size flying boat (PBM-3) with an afterbody having this type of warping showed satisfactory landing stability with a depth of step of 5 percent of the beam and a load coefficient of 0.8 (reference 34). Whether the warping contributes to the satisfactory characteristics is not yet established.

Afterbody plan form.- The plan form of the afterbody appears to be of secondary significance in resistance and porpoising characteristics compared with the length of afterbody, angle of afterbody keel, and angle of dead rise. Changing from a pointed plan form to one with a transverse second step had no significant effect on the hump resistance (reference 9), reduced directional instability at speeds below the hump (references 23 and 73), and increased the air drag (reference 18). Modifying a pointed afterbody to form a cusped plan form reduced the unstable yawing moments at speeds below the hump (reference 10).

Afterbody chine flare.- Afterbody chine flare increases the dynamic lift of the afterbody and reduces both the hump trim and hump resistance (references 21, 22, and 79). If the spray does not break clear at the afterbody chines, suction forces may develop that increase both the hump and high-speed resistance (reference 70). Under these circumstances, the use of chine flare is advantageous and will reduce the landing instabilities (unpublished data).

Position of Center of Gravity and Location of Main Step

Preliminary design.- It has been suggested (reference 28) that the center of gravity be located on a line

passing through the step and inclined between 15° and 25° forward of a line normal to the forebody keel. Tests of powered models of current design indicate that a range from 10° to 20° may be preferable. If the plan form of the step is other than transverse, the centroid of this plan form may be used as an equivalent location (reference 100). Reference 70 suggests that with the airplane approximately in a stalled attitude the center of gravity should be directly above the step. For airplanes with abnormally high angles of stall, the maximum trim expected in landing may be more applicable than the trim at stall.

Effects upon dynamic stability.- Variation in the position of the center of gravity has negligible effect upon the trim limits of stability (references 100 and 106) but has a large effect upon the trim tracks and consequently upon the probability that porpoising will be encountered. A forward movement of the center of gravity lowers the trim track, and lower-limit porpoising (low angles) may be expected at speeds just above the hump. An after movement of the center of gravity raises the trim tracks, and upper-limit porpoising (high angles) may be expected near get-away. Instabilities while on the water may therefore limit the range of positions of the center of gravity that can be used for take-off.

The most forward position of the center of gravity at which a flying boat can operate is generally limited by aerodynamic requirements for control and hydrodynamic requirements for stability. The main step is best located so that the hydrodynamic requirements for stability are met at the most forward position of the center of gravity at which the flying boat will operate. The main step must be located so that, with the center of gravity of the flying boat at its most forward position, lower-limit porpoising can be avoided during take-off. In the event that porpoising does occur, positive trimming moment (up elevators) should be available for increasing the trim to angles above the lower trim limit. This procedure has been used for locating the position of the step during tests in the Langley tanks (references 10, 47, 60, 61, 63, and 100).

Relocation of step to improve stability of model or full-size airplane.- If model or flight tests indicate that the most forward position of the center of gravity which is stable for take-off does not coincide with the position required from aerodynamic considerations, the

location of the step or of the wing may have to be changed. If relocation of the wing is impractical, the step should be moved approximately 1.3 times the distance the position of the center of gravity for take-off must be shifted. The factor 1.3 is the ratio of the gross load of the airplane to the approximate load on the water at speeds and trims at which lower-limit porpoising occurs.

Because of the angle between the forebody and the afterbody, a forward movement of the step results in a reduction in the depth of step that may impair the landing stability. A vertical displacement of either the forebody or the afterbody planing surface is then required in order to maintain adequate depth of step. An after movement of the step results in an increase in the depth of step which may cause a slight increase in the hump trim and resistance but which also tends to increase the landing stability. A forward movement of the step therefore is likely to be more costly and difficult than an after movement of the step. In preliminary design, it is desirable to favor a forward position of the step if further modifications are anticipated.

Depth and Form of Main Step

Depth of step.- An increase in depth of step raises the lower trim limit at low speeds, raises the upper trim limits, and reduces the violence of upper-limit porpoising (references 21, 22, 62, 71, 100, and 103). High negative pressures occur on the afterbody just aft of a shallow step during landing and high-angle porpoising (reference 78). An increase in depth of step increases the landing stability by relieving these suction forces (references 47, 49, 71, 78, 93, and 100). Landing instabilities of models of two airplanes were investigated in the Langley tanks and in both instances increases in depth of step resulted in satisfactory landing characteristics. A similar increase in depth of step of the full-size airplane was accomplished by an after movement of the step, and satisfactory landing characteristics were obtained for both airplanes (reference 71).

Increase in depth of step increases the hump trim and resistance and decreases high-speed resistance (references 7, 21, and 22). The aerodynamic drag of the hull is increased 10 to 15 percent by the presence of the step (references 18, 23, and 43) and the drag

of a transverse step is approximately proportional to the area of the rise of the step (reference 43).

Exceptionally stable landings of a model have been obtained with the depth of step reduced to zero (reference 13).

Ventilation of the step.- In the absence of adequate depth of step for landing stability, the use of ventilation ducts just aft of the step and as near the keel as possible has been successful on models (references 47, 49, 71, 78, 93, 100, and 243) and on full-size airplanes (reference 243). Ventilation does not affect the lower trim limit of stability but raises the upper trim limits slightly (references 47, 49, 78, and 100). When a shallow step is used, ventilation is also effective in reducing a resistance peak that occurs just before hump speed (reference 27). Ventilation apparently has no effect on directional stability (reference 10).

Step fairings.- In an effort to reduce the aerodynamic drag attributed to the presence of a step, fairings have been used aft of the step. Results of tests in reference 18 indicated that the step drag was practically eliminated by a fairing extending back six times the depth of the step. Fairings leaving half the depth of step were less effective while concave fairings, extending back five times the depth of step, saved only one-sixth of the step drag. Tests reported in references 37 and 58 showed similar reductions in air drag by use of step fairings. The addition of a step fairing to one of the Short Brothers flying boats (reference 260) increased the top speed by approximately 5 miles per hour.

The most notable use of step fairings has been on the Short Sunderland flying boat, which has a step that is V-shape in plan form. The hydrodynamic stability in take-off and landing is in general affected adversely by the addition of a fairing to a conventional hull although the characteristics of the Sunderland in this respect appear to be satisfactory (references 14, 18, and 35). Tests of a powered model in Langley tank no. 1 (reference 14) indicated that when a fairing is added to a conventional transverse step the use of ventilation is advisable in order to obtain satisfactory stability. More recent tests (unpublished) of a model with a faired V-shape step indicated that satisfactory stability may be obtained without ventilation and that further investigation of the effects of plan form of the step and camber of the fairing would be desirable.

Plan form of step.- A transverse step is the simplest form of step and has been used on most flying boats and seaplanes. Other plan forms of step, however, have been used on full-size airplanes or tested on models. Some of these forms are shown in figure 9. The effect of

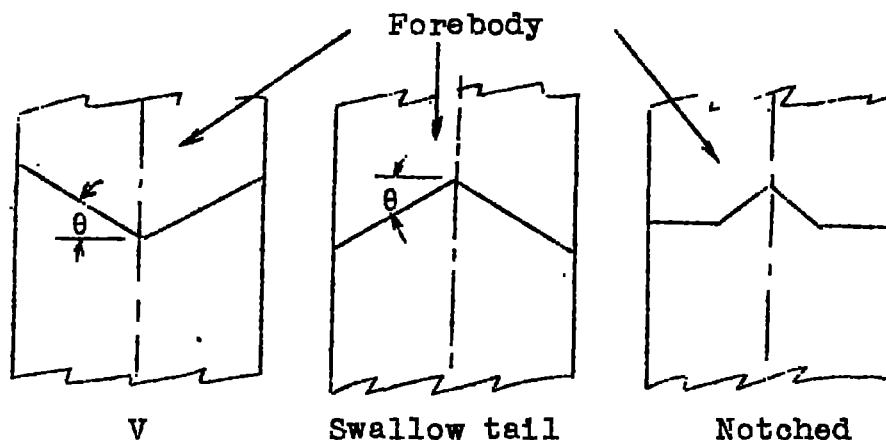


Figure 9.- Plan forms of step (θ , angle of V or swallow tail).

change in the plan form of the step on the landing stability cannot be isolated because the landing stability is so closely associated with the depth of step. Tests described in reference 77 indicate that, with the same depth of step at the keel, the landing stability of a model with a transverse step and with a 30° V-step are comparable.

The lower trim limit is not greatly affected by changes in plan form of the step (reference 100) but in all probability the upper limits will be shifted in the direction expected from the change in the depth of step.

Side Steps and Skegs

When operating at overloads, several present-day flying boats are directionally unstable at low taxiing speeds. Unstable yawing moments are increased by the flow of water over the sides of the afterbody and tail extension. The directional control available by throttling engines on one side lowers the reserve thrust and increases the time of operating in the yawing region.

One means of reducing the directional instability by breaking the undesirable flow is by use of vertical steps on the sides of the afterbody. Such steps reduced unstable yawing moments on a model and were successfully used on the full-size airplane (reference 82). The directional instability of a model was reduced more effectively by multiple side steps than by a single side step (unpublished data).

The addition of skegs to the afterbody and tail extension reduced unstable yawing moments. As the speed increased, the effectiveness of the skegs decreased as they came out of the water (reference 74). Several arrangements of skegs on the full-size airplane were tried, and the results obtained were similar to those observed for the model. It should be emphasized that skegs, steps, and spoilers may substantially reduce the unstable hydrodynamic moments but may not be completely effective in stabilizing an airplane in which rotation of the slipstream contributes an additional yawing moment.

Tail Extension

Although the function of the tail extension of a flying boat is similar to that of the tail extension of a comparable landplane, the additional problems introduced by the flow of water over the tail extension and the necessity for spray clearance complicate the design. The flow of water over the tail extension may increase the violence of upper-limit porpoising, may introduce landing instability at high trims, may increase the hump trim and resistance, and may contribute to directional instability.

The addition of a planing surface or spray strips on the tail extension may be necessary to prevent excessive wetting of the horizontal tail surface or tail turret (references 74 and 79). The planing action of the tail extension may decrease the hump trim and resistance by developing dynamic lift (references 39 and 79).

Although the flow of water over the tail extension may contribute to the directional instability at low speed, the removal of the tail extension does not eliminate hydrodynamic directional instability (references 23 and 56). An increase in vertical clearance of the tail extension, a negative-dihedral hydrofoil on the tail extension, and

an inverted-V cross section on the tail extension were tested on a model and found to be only partially effective in counteracting yawing tendencies (unpublished data). A planing surface on the tail extension of a model caused no reduction in unstable yawing moments and increased the range of speeds over which they occurred (reference 74).

FLOATS FOR SEAPLANES

Much of the preceding discussion relative to hulls is also applicable to seaplane floats. In particular, the planing areas of hulls and floats are generally similar. The discussions of the geometric parameters of hulls relating primarily to stable planing motions will therefore not be repeated in the sections on floats. In the design of floats special considerations arise from the lower reserve buoyancy, the relatively greater distance from the center of gravity to the keel, and the absence of a tail extension. For twin-float designs an additional consideration is that the distance between the floats must be chosen to insure transverse static stability.

Over-all proportions and shape.- Adherence to the requirements for longitudinal static stability usually results in length-beam ratios for floats that are larger than those customarily used for flying-boat hulls - averaging about 7.35 for float seaplanes as compared with 5.27 for hulls (from tabulations in reference 57). The average length-beam ratio currently used for twin floats appears to be somewhat greater than that for single floats.

The shape of the bow of a float should be generally similar to that of the hull, but the low height-beam ratio restricts the possible variations in the shape of the bow of a float. Lines of representative floats are included in references 123, 139, 140, and 143, together with data regarding the aerodynamic and hydrodynamic characteristics of a wide range of changes in shape of the bow.

Dead rise.- The effects of changes in dead rise are generally the same for both hulls and floats. Aerodynamic and hydrodynamic data are presented in reference 140 for floats having angles of dead rise of 20° , 25° , and 30° . In American practice the average dead rise for floats appears to be higher than the dead rise for hulls (reference 57).

Statics.— It has been the practice in float design to fix the volume of the floats so that the buoyancy is some predetermined percentage of the gross load, varying between 180 and 200 percent (references 120 and 121). In any case there should be enough excess buoyancy to prevent the bow from submerging at low taxiing speeds. A large excess buoyancy allows a lower and more streamline form of bow to be used. The high engine torque inherent in racing seaplanes created such an eccentricity of loading in the case of the S.5 (reference 256) that it was found necessary to make one float larger than the other for satisfactory spray characteristics.

The length of floats must be sufficient to assure static longitudinal stability. According to reference 154, the longitudinal metacentric height GM for either single or twin floats is given with sufficient accuracy by the empirical equation

$$GM = \frac{K_2 n B L^3}{\Delta}$$

where

- n number of floats (that is, one or two)
- B beam of each float, feet
- L over-all length, feet
- Δ gross weight of seaplane, pounds
- K₂ a constant normally varying between 1.90 and 2.40 with an average value of 2.10

The Canadian requirements (reference 120) for twin-float seaplanes specify that the longitudinal metacentric height shall not be less than

$$6\sqrt[3]{D}$$

where D is the total displacement of the seaplane in cubic feet. As the reserve buoyancy is determined from other considerations, the requirements for static longitudinal stability indicate that the length-beam ratios of twin-float arrangements will be larger than those of single-float arrangements. Single-float seaplanes have

length-beam ratios varying from 5 to 7 while twin-float seaplanes have length-beam ratios varying from 7 to $8\frac{1}{2}$ (reference 57).

Effect of spacing between floats.- Tests of a model of the S.5 twin-float seaplane (reference 256) show increases in resistance with float spacing up to 20 percent, apparently caused by heavy spray wetting the tail plane and other parts of the structure. Unpublished data from Langley tests for spacings ranging from 2 to 5 beam lengths, keel to keel, showed small differences in resistance that were almost within the accuracy of measurement.

Air drag of floats.- Results of wind-tunnel tests of seaplane floats show that the form of the bow strongly affects the minimum drag and the variation of drag with angle of pitch. The angle of afterbody keel affects the angle of minimum drag and is of practical significance in the choice of a configuration for which the minimum drag will occur within the desired range of flying speeds (reference 139).

Tests of a full-size float seaplane in the Langley full-scale tunnel (reference 145) indicated that the maximum speed would be increased from 307 to 336 miles per hour by removing the main float (77 percent excess buoyancy). The seaplane had a power loading of 5.9 pounds per horsepower and a wing loading of 27.2 pounds per square foot. Tests of four full-size floats in the Langley propeller-research tunnel (reference 127) indicated that a radical change in the design of the floats was required to obtain significant reductions in the air drag. Reducing the depth of step to zero decreased the minimum drag about 16 percent. Adding a faired tail extension to a float with a blunt stern reduced the drag 8 percent. The flow of air over the floats was shown to be so turbulent that minor refinements such as flush rivets and recessed fittings would not appreciably reduce the drag.

Dynamic stability of float seaplanes.- Porpoising and skipping have appeared to be of much less practical significance in operating float seaplanes than in operating flying boats. Although differences have not been carefully analyzed, two differences between the types are noteworthy in comparing the stability characteristics: the pitching

radius of gyration of a float seaplane is generally larger than that of a comparable flying boat; and recent practice has been to provide relatively deeper steps on floats than on hulls. Another consideration is that for military use a number of the different types of float seaplane have had considerably lower power loadings than the patrol and cargo types of flying boat.

LATERAL STABILIZERS

Types of lateral stabilizer.- Three types of lateral stabilizer have been used in the past: inboard floats, stub wings, and wing-tip floats. Neither inboard floats nor stub wings have been used, however, in recent designs. Inboard floats are located inboard of about one-third the semispan of the wing and therefore must be larger than wing-tip floats in order to develop the same righting moment. Inboard floats usually have a shallow draft at rest whereas wing-tip floats are generally located to clear the water at high speed and, because of their location, only one wing-tip float contacts the water at rest. Stub wings (reference 156) extend outward from the chine near the main step in the form of aerodynamic wings of low aspect ratio. The evidence seems to be in favor of wing-tip floats for lateral stabilizers because they are relatively small, their maximum restoring moment is developed at small angles of heel, and they are not influenced by the flow of water produced by other parts of the seaplane.

Hydrodynamic data concerning wing-tip floats.- The usual consideration in the choice of the shape for a tip float has been that any lines suitable for a main float are adaptable for a tip float (reference 147). The contour of the bottom of a tip float is generally made to resemble that of a V-bottom hull and the required volume is then disposed in a manner either to obtain minimum aerodynamic drag or to comply with other requirements (for example, retraction) of the specific installation.

The performance characteristics during operation at low speed have been determined for a number of typical designs of wing-tip floats. The data have been obtained from tests in towing tanks in the speed range at which wing-tip floats are necessary. Some of these data are

reported in references 74, 152, 153, 160, and 164. A significant result of the tests has been the placing of emphasis upon the importance of designing the lines above the chines to avoid losing lift at large drafts and thereby to prevent "digging in" of the float. Wing-tip floats have been built with steps to incorporate a satisfactory planing surface on a form that will have low air drag in flight. Later tests, however, have shown that low air drag and satisfactory performance at low speed can also be realized without a step (reference 164).

Captain H. C. Richardson has emphasized in letters to the NACA that the behavior of a tip float in drifting astern is of special importance in the event of a forced landing. His experience in "sailing" a disabled flying boat, the NC-3, for a distance of about 200 miles in the Atlantic Ocean (reference 211) led to the conclusion that satisfactory seaworthiness requires the tip float to be free of any tendency to "dig in" when making sternway. Specific test data are not available for tip floats moving astern but it has appeared that a float with a step is advantageous because the "afterbody" may be sloped upward to develop lift.

Hydrodynamic characteristics of stub wings.- Interference between the water flow around the hull and the stubs affects the resistance, the trimming moment, the dynamic stability, and the transverse static stability of the flying boat. Tests of a limited number of configurations indicate that stub wings reduce the hump speed without significantly affecting the magnitude of the hump resistance, reduce the trim at zero applied moment (reference 146), reduce markedly the region of speeds and trims in which low-angle porpoising occurs, and adversely affect the upper trim limit of stability (reference 163). Data regarding the effects of variations in the position of stub wings are given in references 146, 149, and 151. At rest, stub wings develop their maximum righting moment at very large angles of heel; hence, the righting moment may be insufficient when the hull is lightly loaded. Underway, the stub wing is subject to the influence of the bow wave that leaves it free of "solid" water through a small range of speeds. If the flying boat with stub wings is not accelerated rapidly through this speed range, it may heel sufficiently to submerge a wing tip.

Air drag.- The air drag of tip floats amounts to $\frac{1}{32}$ to 8 percent of the total drag for a number of flying boats that have wing-tip floats currently considered

well streamlined. Reference 150 presents data showing the air drag of wing-tip floats to be of the same order of magnitude as the air drag of well-faired unretracted landing gear on comparable landplanes. Reference 18 contains a comparison of the air drag of six configurations of flying-boat hulls differing only in the arrangement of the lateral stabilizers. (See fig. 10.) Results of tests

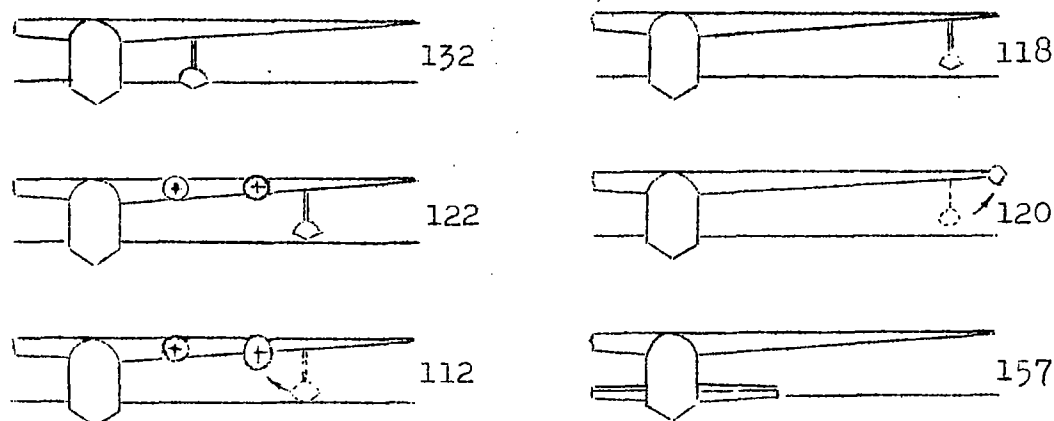


Figure 10.- Comparative diagrams of air drag of hull and lateral stabilizers. Numbers give drag relation to basic hull, taken as 100 (from reference 18).

of four different types of conventional wing-tip float (reference 153) led to the significant conclusion that the chines of an unretracted wing-tip float should be aligned with the air flow in cruising flight to avoid excessive air drag. The air drag of partially retracted tip floats may be estimated from data concerning protuberances on the lower surface of the wing (references 157 and 158).

Present status of design criterions.- Several different specifications and criterions have been used in the past for lateral stabilizers (references 51, 59, and 251). Current American practice conforms in general to the specifications given in references 6 and 147. The specifications present formulas for computing the size of conventional lateral stabilizers for obtaining an arbitrary minimum lateral stability at rest. Current practice is to provide the righting moments needed to

counteract the upsetting moments due to gravity and cross wind and to provide an additional reserve buoyancy determined on the basis of past experience. For the larger sizes of flying boat the reserve buoyancy is very much larger than either of the other two allowances (reference 162) and a more detailed examination of the design requirements than heretofore employed is considered necessary if the structural and aerodynamic efficiency are not to be unduly impaired by the tip floats. In reference 155, the numerous upsetting moments including propeller torque, unsymmetrical slipstream, and wave slope are listed in outlining a procedure for defining in detail the necessary buoyant and dynamic characteristics of tip floats. There is some indication that, if the tip floats can be designed to have suitable dynamic reaction when submerged, smaller tip floats than those currently used on large flying boats may be adequate.

Unconventional forms of stabilizers.- A large reduction in drag of a fixed tip float might be realized by using a streamline spindle fitted with a hydrofoil instead of a conventional shape. Stabilizers of this kind are shown in reference 166 and test results are presented in references 159 and 161. A comparison of the drag of the streamline shape with that of a conventional wing-tip float is made in reference 145. A streamline float of rectangular cross section with a hydrofoil was used on the ND-1 float seaplane but test results do not appear to be available. Until adequate data are available for predicting the hydrodynamic lift and drag of hydrofoils, this type of configuration cannot be designed with assurance that the high-speed characteristics will be satisfactory.

Broad, shallow floats having the form of a somewhat distorted spherical segment have been suggested (reference 150). Unpublished data from tank tests indicate that, although retraction would be facilitated, this shape would give rise to very large dynamic lift that would necessitate a type of oleo strut for operation in rough water. Rapid retraction and extension would permit the wing-tip floats to be located out of danger at high speed.

A very interesting possibility for obtaining lateral stabilization, especially for high-performance single-engine seaplanes, is by use of the dynamic and buoyant

properties of the wing located in the low-wing position, as described in the section entitled "Unconventional Configurations."

Emergency devices.- When it is necessary for a seaplane to remain at rest under abnormally severe conditions, emergency stabilizing devices can be provided in the form of sea anchors (trimming buckets, canvas bags filled with water and hung in the water from an outboard position on the wing, as shown in reference 32) or inflatable devices.

AERODYNAMIC AND PROPULSIVE CONSIDERATIONS

The aerodynamic and propulsive arrangements for flying boats are primarily determined by their flight performance specifications, which are beyond the scope of this report. Hydrodynamic considerations that may modify these configurations are discussed in this section.

Wing.- The area of the wing is determined by the service conditions for which the flying boat is designed. The main effect of high wing loadings on the take-off performance of a flying boat appears in the higher get-away speeds. As the get-away speed becomes higher, the resistance at high speeds becomes more significant. Computations show that take-off performance is improved by increasing the aspect ratio (reference 167). The angle of incidence of the wing is of significance in relation to the hump trim and the trim of the hull in flight. When the high-speed resistance is critical, the setting that gives best take-off characteristics may be taken as approximately that which gives minimum total resistance at 85 percent of the stalling speed (references 90 and 167).

The general practice in airplane design is to mount the engine nacelles on the wing with the thrust line approximating the chord of the wing. Current practice shows that if the propellers have adequate clearance wings and flaps are adequately clear. (See section entitled "Propellers.")

Flaps.- The effect of flaps on the take-off is especially pronounced on airplanes having high wing and power loadings. Although flap deflection increases the

total resistance, it generally improves the take-off performance by lowering the stalling speed. The optimum take-off can be made by taxiing to high speed with the flaps up and deflecting them part way for take-off (reference 170). Deflecting the flaps reduces the load on the water and causes a bow-down moment (reference 47). By reduction of the load on the water the trim limits are generally lowered slightly, particularly at high speeds. The bow-down moment requires up-elevator deflections to counteract it and shifts the stable range of center-of-gravity positions aft (reference 166).

The lift on the wings of a flying boat moored on the water may be reduced by flap-type spoilers mounted on the upper surface of the wing between 5 and 20 percent of the chord with no gap between them and the wing surface (reference 171). This device should be useful if an airplane having a low wing loading is to be moored in a high wind.

Tail surfaces.- The horizontal tail is usually mounted rather high to clear the spray. At low speeds, the roach may wet the tail heavily. At higher speeds, the spray is higher at the tips of the tail than at the root so that the use of considerable dihedral angle may be advantageous; in fact, this dihedral angle may be carried to the extreme of employing a V-tail (reference 169). Approximately the same total area is required but there is a possibility of reducing the air drag by eliminating one intersection with the fuselage. The control system presents a complicated design problem.

The aerodynamic stability derivatives have some effect on hydrodynamic stability (references 46 and 106). It is pointed out in reference 46 that for the cases considered therein it was quite impossible to neglect the aerodynamic factors although the hydrodynamic effects appeared to be much more important than the aerodynamic factors.

Variations from the usual size of the horizontal tail have a small effect on the lower trim limit of stability. Reference 22 shows that increasing the damping in pitch due to the horizontal tail M_q decreases the lower limit of stability. The decrease is small at low speeds and is appreciable at high speeds. At a given high speed, the effect of increasing tail area

becomes less marked as the tail damping increases and is not very significant at the normal values of tail damping. These trends are also indicated in references 53 and 106. The tail damping has a negligible effect on the upper branch of the upper trim limit of stability.

No data have been published on the amount of yawing moment required of the vertical tail (or of water rudders) to maintain control throughout the taxi and take-off run. Unpublished data indicate that a model of a flying boat with a gross-load coefficient of 1.05 at a speed coefficient of 2.6 required a yawing-moment coefficient C_n of 0.12 to maintain a straight course. The yawing moment coefficient

$$C_n = \frac{\text{Yawing moment}}{wb^4}$$

where w is specific weight of water and b is the beam.

Propellers.- On some heavily loaded flying boats, spray from the forebody enters the propellers during a short range of speeds just prior to hump speed. For any given conventional flying boat, both the intensity of the spray and the width of the speed range when the spray is in the propellers increase with increasing gross load (reference 61).

The inflow of air to powered propellers picks up spray that would not hit the windmilling propellers (reference 70). Some spray profiles for unpowered models are given in references 20 and 254.

The right-hand rotation of propellers tends to make the flying boat yaw to the left. During take-off, the hull is directionally unstable just below the hump. A heavily loaded flying boat with right-hand propellers often makes uncontrollable turns to the left at this speed. With opposite rotation of the propellers, the yawing characteristics are symmetrical about zero yaw. Propellers turning inboard at the top provide slightly better rudder control than those turning outboard.

Reference 78 shows that the effect of power on trim limits and center-of-gravity limits of a model is large. The effect of the slipstream and thrust is to change the load on water and the trimming moment and to influence

the water flow around the hull. Decreasing the power loading of a flying boat increases the acceleration during take-off but reference 50 shows that there is a relatively small change in the stable center-of-gravity range with change in acceleration.

Jet propulsion.- Jet assistance has enabled flying boats to take off more quickly in rough water, to take off in a shorter distance, or to take off with loads greater than those possible with normal engine power. The assisting jets are either of the powder type, which may be dropped after take-off, or of the type in which liquids are forced into a combustion chamber. The liquid-type jet generally operates for longer periods of time but requires that more equipment be carried in the airplane throughout the flight. An advantage of this type of jet is that it may be turned on and off as desired.

The location of the assisting jets is not particularly critical. They should be so arranged that the line of thrust passes through, or slightly below, the center of gravity of the airplane so that when the thrust ceases no great change in the balance of the airplane will result. One liquid-type jet has operated successfully under water (reference 165) but no information is available as to the behavior of the powder-type jet when submerged.

Jet engines could be mounted closer to the water than engine-driven propellers, provided a suitable location for the air inlet can be found. There is no information as to the extent that the inflow of air will pick up spray or to the extent that spray will damage the interior of the jet motors if it is allowed to enter with the air. Jet engines designed to produce a given thrust at flight speeds may be at a disadvantage during take-off when compared with normal propellers because of differences in the manner in which thrust varies with speed. The jet engines for use on high-speed airplanes would probably have sufficient thrust for take-off.

UNCONVENTIONAL CONFIGURATIONS

Tunnel bottoms.- Hull forms with a tunnel bottom (an inverted V) have been proposed occasionally because

the amount of spray thrown out laterally is exceptionally small (references 3, 172, and 177). Configurations of the types that have been tested present a difficult problem in avoiding excessive air drag. If the spray is confined to the tunnel, the afterbody may be wet excessively unless large clearance is provided. A model with a forebody having an inverted-V cross section at the bow with a transition to normal V-bottom about halfway along the forebody was tested at the Short Brothers Tank (reference 260). This unusual form had very good spray characteristics and would presumably have acceptable resistance and stability characteristics. Wind-tunnel tests and structural studies showed, however, that the air drag and the weight would be excessive.

Asymmetrical floats.- The spray between the floats of a twin-float single-engine seaplane resulting from the meeting of the two bow blisters sometimes enters the propeller in excessive amounts. A pair of floats was designed (reference 124) having the planing bottoms arranged on the outer sides of the floats (fig. 11).



Figure 11.- Asymmetrical float
for twin-float seaplane,
section at step.

It was found that these floats were clean running and compared satisfactorily with conventional floats with regard to porpoising, water resistance, and directional stability. Modifications intended to reduce the air drag of the asymmetrical floats introduced directional instability.

Planing tail.- A form of hull that inherently has some desirable characteristics is being developed by

tests of models in Langley tank no. 2. Figure 12 shows a typical configuration with a very deep step that is

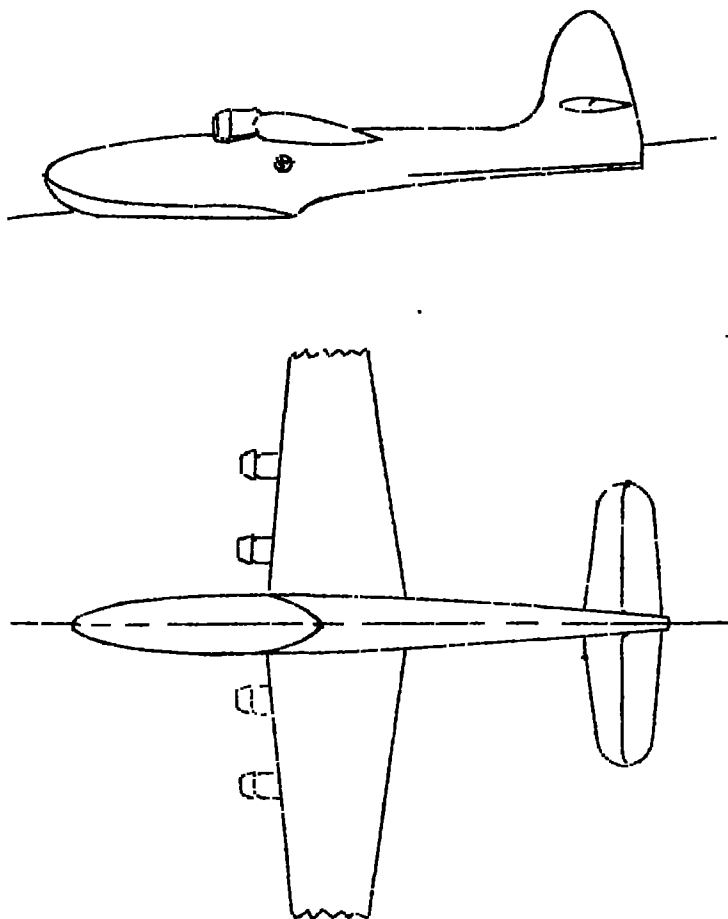
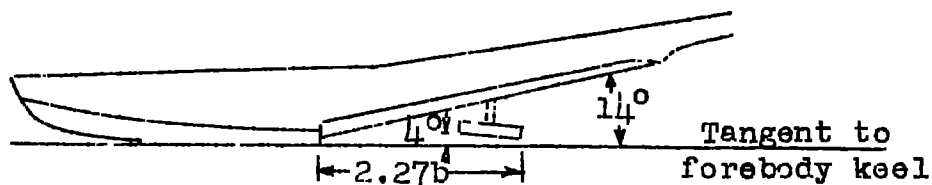


Figure 12.- Planing-tail configuration.

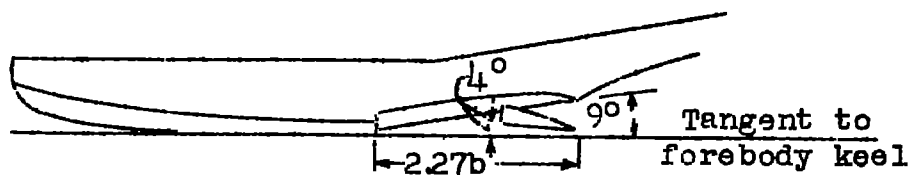
pointed in plan form combined with a long afterbody. Preliminary tests (reference 176) and further tests of modifications similar to those in figure 12 showed that the hump resistance was lower than that of a conventional hull ($\frac{\Delta}{R} = 6.5$ compared with $\frac{\Delta}{R} = 5$). Tests of a dynamic

model indicated that satisfactory stability characteristics may be expected (unpublished data). Limitations on the usable space aft of the center of gravity may be undesirable for some types of service.

Planing flaps.- Retractable planing flaps have been suggested for use on the afterbody in a manner that would allow an unusually high angle of afterbody keel (fig. 13(a)). The flap would perform the normal function of the afterbody at speeds through the hump speed. At planing speeds the flaps would be retracted to prevent high-angle porpoising from occurring in the usual range of trim. Tank tests were made at Stevens Institute of Technology to determine several configurations that would have suitable hydrodynamic characteristics (reference 178). The structural weight, the aerodynamic effect of a high angle of afterbody keel, and the necessity for adjusting the flap during take-off present problems that introduce some doubt as to the practical possibilities of this type of flap. Reference 178 includes results obtained from tests of a hull with a conventional afterbody to which was added a planing flap near the sternpost (fig. 13(b)). The results of the tests showing that



(a) High afterbody.



(b) Conventional afterbody.

Figure 13.- Planing flaps.

high-angle porpoising was suppressed were not confirmed in tests (unpublished data) of a similar configuration on a powered model in Langley tank no. 1.

Float-wing designs.— Tests have been made of models (references 174 and 175) and of a full-size glider having a conventional hull combined with a wing placed sufficiently low to provide suitable transverse stability on the water (fig. 14). Hydrodynamic characteristics of the full-size glider were reported to be satisfactory



Figure 14.— Float-wing glider.

provided the flaps were not deflected while in contact with the water. A preliminary design of a float-wing seaplane that would employ a pusher propeller in a transverse plane near the trailing edge of the wing is known to have been made. If a suitable structure were provided for the power unit and for those portions of the wing and flaps subjected to water loads, it appears that a high-performance seaplane with parasite drag practically equal to that of an equivalent landplane could be developed.

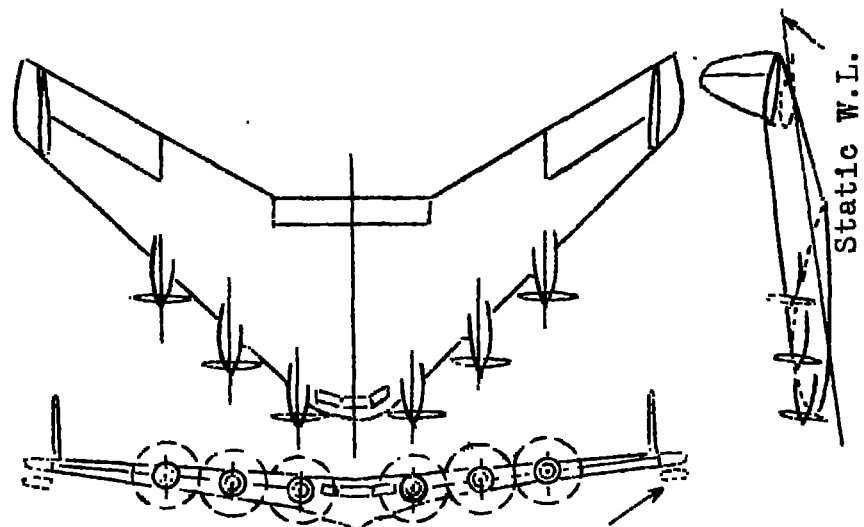
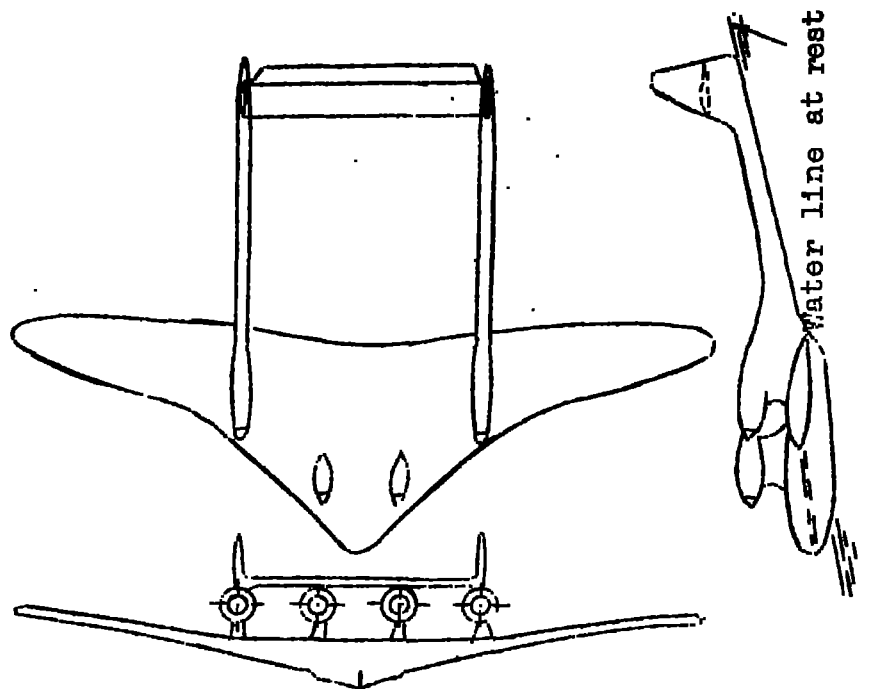
Hull-less designs.- In reference 173 several designs are proposed, including a flying wing, in which the hydrodynamic and flotation requirements would be incorporated as primary components of the wing. Preliminary results of tank tests and of structural studies are cited to support the belief that large seaplanes can be built in one of the proposed forms with considerable reduction in weight and in parasite drag compared with conventional flying boats and landplanes. Two of the proposed configurations are shown in figure 15.

HYDROFOILS

The application of hydrofoils to serve as a type of landing gear on seaplanes or as auxiliary lifting devices on wing-tip floats has long been an interesting possibility with reference to the reduction of air drag and the simplification of structural problems. It has appeared that hydrofoils when compared with planing hulls offer some possibility of reducing the structural weight and the hazards associated with impacts in rough water. Although hydrofoils have been successfully employed on numerous seaplanes with a relatively low stalling speed (reference 186), an evaluation of their potential use on seaplanes that must operate on the water at speeds above 60 miles per hour is hindered by inadequate information regarding the influence of cavitation.

Hydrofoils having cambered sections selected to delay cavitation as much as appeared practicable were towed in Langley tank no. 1 at depths up to 5 chord lengths and at speeds up to 60 miles per hour. As the speed was increased from 40 to 60 miles per hour, the results showed that:

- (1) The angle of zero lift increased about 3°
- (2) The maximum lift-drag ratio decreased steadily from about 16 at 40 miles per hour to 8 at 60 miles per hour (references 181, 189, and 201)
- (3) Cavitation caused vibration that became more severe with increased speed



Floats for longitudinal static stability are retracted to form wing tips

Figure 15.- Hull-less design from reference 173.

Similar trends were obtained in water-tunnel tests of planoconvex circular-arc sections in which extensive cavitation was obtained (reference 200). The theoretical results in reference 183 are in partial agreement with the trends given but there is still considerable doubt as to the magnitude of the influence of cavitation. There is some indication that a hydrofoil in cavitating flow will have more favorable lift-drag ratios if the lower surface is flat rather than convex. Tests in a water tunnel (reference 194) indicated that slots in a hydrofoil were ineffective in preventing cavitation.

Ladderlike arrangements of hydrofoils with dihedral of about 20° that have been used on seaplanes and on surface boats apparently offer satisfactory stability, but the associated struts and interference effects are significant sources of drag and spray (references 180, 185, 186, and 192). Monoplane hydrofoils are likely to suffer abrupt and large changes in lift and drag when close to the free water surface (references 180, 181, and 190). The severity of this type of instability is less for the higher angles of dihedral because of the more gradual reefing action as the hydrofoil passes into or out of the water. Systems of monoplanes designed to overcome this difficulty of operating near the water surface have been proposed and tested at low speeds by Tietjens (reference 198) and by Grunberg (references 185 and 191). Further investigation under conditions in which full-scale cavitation is represented are required, however, before a practical design of a monoplane configuration for a seaplane may be carried out with full assurance that stability and efficient lift-drag ratios will be achieved (reference 196).

PILOTING AND HANDLING

A few clearly established principles can be outlined that will assist the pilot of a seaplane of conventional design to take off in the least time and distance possible and at the same time to avoid much of the danger associated with porpoising, yawing, and skipping. The required technique for operation in smooth water can be simply stated; but for operation in rough water the importance of porpoising, yawing, and skipping as compared with the importance of the waves to be encountered

in any particular instance must be evaluated on the basis of the personal observation and experience of the pilot. The principles for operation in smooth water have been sufficiently well established by tests of models and full-size aircraft to justify a revision of some of the practices that appear to be currently accepted.

Glassy water.- References 205, 206, and 211 point out the difficulty of accurately observing the height above the surface of the water as a seaplane approaches a landing on glassy water, especially if there is a low-hanging mist. No satisfactory technique or instrumentation appears to be available that will enable the pilot to judge with confidence the point of contacting the water surface. Terrain clearance indicators might be of considerable value if they could be made to indicate accurately at very low altitudes. Possibly absolute altimeters will come into sufficiently wide use to justify their development to a stage at which they can be used for glassy-water landings.

Take-offs from glassy water have frequently been reported to be more difficult than those from choppy water. Definite data regarding these observations are not sufficient to justify very definite conclusions. Differences of opinion regarding these observations are sufficiently great to justify a brief series of tank tests or flight tests in which the influence of wind (which generally accompanies rough water) and the influence of trim may be isolated from the effects of small waves on the resistance during take-off.

Stability.- Instructions to pilots regarding porpoising should clearly distinguish between the low-angle type and the high-angle type. The usual instructions to apply up elevators whenever porpoising occurs (references 205, 206, and 211) are applicable only to the low-angle type. Recovery from the high-angle type of porpoising calls for down elevators.

Uncontrollable yawing of some flying boats may occur in either of two speed ranges. The yawing at speeds approaching the hump is associated with an unstable type of flow over the bottom and sides of the afterbody and may be aggravated by unsymmetrical slipstream over the tail. A disastrous type of yawing may occur at speeds near get-away if the hull is allowed to trim too low (reference 40).

Rough water.- A PBM-3C flying boat has recently been tested by the U. S. Coast Guard to investigate the merits of different piloting techniques in rough water and to evaluate the hazards that are involved (reference 203). It is understood that wave heights ranged from 8 or 10 inches up to about 15 feet during the course of the tests. The tests were limited to the one airplane and to the sea conditions prevailing off the coast of southern California, but the results provide a noteworthy basis for setting up general principles for piloting in rough water. Results of the tests indicated that before making a landing in the open sea the pilot should fly at different altitudes to observe the different wave systems that may be present and in general to select the direction of run and the area that will result in the least number of severe wave impacts. For winds of less than 20 knots the most favorable direction was found to be parallel to the crests of the swells. Down-swell landings were considered feasible but more severe than along-swell landings. If the wind is greater than 20 knots, the recommended direction for the run is into the wind. Drift in a cross-wind landing was found to be of little practical consequence. Previously held fears of danger from dragging a wing-tip float in a swell on the beam or from sideslipping down the slope of a wave were not substantiated. With a complicated sea, the pilot should choose a direction for landing or take-off that will avoid heading directly into any wave system and will at the same time keep the wind as nearly ahead as possible.

Jets of the solid fuel type were used in some of the take-offs and found to be a very useful adjunct in rough-water operation. In several instances the use of jets at dangerous moments was believed to have saved the airplane from severe damage.

Reversible propellers.- Maneuvering to a buoy or other mooring device has been greatly facilitated by the use of reversible propellers that permit braking and maneuvering in close quarters. Reference 209 describes the maneuverability of a PB2Y-3 with reversible-pitch propellers and states that those propellers reverse in from 10 to 15 seconds, which is considered slower than desirable. Two of the four propellers are therefore continuously in reverse and the maneuvering in any desired direction is accomplished by manipulation of the throttles.

Depth of water.- Tests of models have indicated that the water resistance is practically unaffected by variations in depth for depths greater than about 1 beam length. At lesser depths the hump resistance may be considerably more than that for deep water (references 210 and 244).

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Langley Field, Va.

B I B L I O G R A P H Y

Reports that are not generally available for distribution, either for security, proprietary, or other reasons, are marked with an asterisk. In special cases requests for these reports may be granted. Any such requests should be directed to the Office of Aeronautical Intelligence of the National Advisory Committee for Aeronautics.

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